SURF ZONE WAVE KINEMATICS

Frank Lee Bub

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

SURF ZONE WAVE KINEMATICS

by

Frank Lee Bub

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Thesis Advisor: E. B. Thornton

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than the measured spectral peak and showed a phase five degrees ahead of the measured horizontal water particle velocity. Celerity calculations between adjacent wave profiles over the coherent frequency range of the spectra showed that the wave phase speed was not frequency dependent and was predictable by the linear theory shallow water approximation. The finding that a dispersive linear wave system predicts the wave kinematics, while a non-dispersive system was observed, suggested a contradiction and was discussed. Capacitance wave gages and electromagnetic flow meters were found to be excellent instruments for use in the surf zone.

Surf Zone Wave Kinematics

by

Frank Lee Bub
Lieutenant, United States Navy
B. S., Lehigh University, 1968

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OCEANOGRAPHY

from the

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September 1974

ABSTRACT

Measurements of three wave surface profiles in a line perpendicular to the beach extending across the breaker line and a set of horizontal and vertical water particle velocities at the breaker line were taken in a mild surf and spilling type breakers. The application of a linear wave theory transfer function to the surface profile spectrum resulted in a calculation of the horizontal water particle velocity spectrum which was 13 percent lower than the measured spectrum peak and showed a phase five degrees ahead of the measured horizontal water particle velocity. Celerity calculations between adjacent wave profiles over the coherent frequency range of the spectra showed that the wave phase speed was not frequency dependent and was predictable by the linear theory shallow water approximation. The finding that a dispersive linear wave system predicts the wave kinematics, while a non-dispersive system was observed, suggested a contradiction and was discussed. Capacitance wave gages and electromagnetic flow meters were found to be excellent instruments for use in the surf zone.

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LIST OF SYMBOLS

A - Wave amplitude (m)

C - Wave celerity or phase speed (m/s)

f - Frequency (Hz)

g - Gravitational constant (9.8 m/s)

H - Wave height (m)

H_s - Significant wave height (m)

h - Mean water depth (m)

k - Wave number (m^{-1})

S(f) - Power density spectrum (m^2s or $(m/s)^2s$)

t - Time (s)

u - Velocity in horizontal direction, positive shoreward (m/s)

w - Velocity in vertical direction, positive upward (m/s)

x - Horizontal distance (m)

z - Vertical distance (m)

η - Vertical displacement of water surface from mean water depth (m)

σ - Angular frequency ($2\pi f$) (s^{-1})

ϕ - Phase

$_{-m}$ - Measured value, as applied to spectrum

$_{-c}$ - Calculated value, as applied to spectrum

I. INTRODUCTION

A. OBJECTIVES OF THE EXPERIMENT

The kinematics of wave forms and water particle velocities in the surf and breaker zones has been an enigma to science for many years. Laboratory studies have established the fact that the linear solution to the wave equations, which applies well to waves of moderate height in deep water, cannot fully describe monochromatic waves and associated water particle velocities during the breaking of waves. This experiment was designed to measure surface profiles and water velocities in the breaker zone and compare the results with present theory. As a secondary objective the accuracy and usefulness of capacitance wave gages and electromagnetic flow meters in the surf environment were to be evaluated. The experiment also added to a data bank of measurements taken in the surf zone for studies being conducted at the Naval Postgraduate School.

It is expected that the data obtained will ultimately contribute to the establishment of a theory which will accurately predict various wave parameters from one set of measurements taken in the breaker zone.

B. APPROACH TO THE PROBLEM

Measurements of water surface profiles at four locations in a line perpendicular to the beach and two sets of horizontal and vertical water particle velocities at the

breaker point were attempted during this research. An energy-density spectrum was calculated for each data set and coherence and phase were calculated between data sets. A wave profile spectrum was converted to horizonal and vertical velocity spectra using linear theory transfer functions. These spectra compared with the measured velocity spectra taken at the same point. Solitary wave theory was also compared to the measured results. The assumption that the processes in the breaker zone are stationary and ergotic was investigated.

C. PREVIOUS WORK

This experiment is a continuation of work conducted at the Naval Postgraduate School by Steer (1972) and Richardson (1973) under the direction of Thornton (1968, 1972). The problem of taking direct measurements in the surf zone was first attacked by Inman (1956) who infered water particle velocities from measured drag forces under the waves. Miller and Zeigler (1964) measured in situ particle motions using acoustic and electromagnetic current meters. Walker (1969) made the same type of measurements using the propeller type flow meters. Wood (1973) measured waves and currents in the surf zone using movies of dye movement and capacitance wave gages. Work by Dean (1974) gives an analysis of various wave theories applicable in the surf zone.

II. DATA COLLECTION AND PREPARATION

A. EQUIPMENT

Measurements were taken using two electromagnetic flow meters, three capacitance wave height gages, and one resistance wave height gage. All equipment was calibrated, in the laboratory, prior to the experiment.

The two flow meters were Marsh-McBirney Model 721 Electromagnetic Current Meters. The flow meter operation is based on Faraday's principal of electromagnetic induction. Each probe measures water velocity in two orthagonal directions, horizontally (shoreward) and vertically. Measurement accuracy was determined to be ± 0.02 m/s during calibration. A carpenters level was used to establish axis alignment in the field with an estimated error of ± 5 degrees.

The flow meters were calibrated in the laboratory using an oscillating platform attached to an eccentric arm 50.72 cm long driven by a variable speed motor using the method of Steer (1972) and Richardson (1973). The speed of the motor was determined using a stopwatch to measure the time required for five revolutions and then making a comparison with the average of ten maxima voltage outputs measured on a strip chart recorder. Because the platform became unstable at velocities above 1.3 m/s (0.4 Hz), calibration stopped at this point. The flow meter calibration plots are shown

in Figure (1). A linear regression was performed on the actual velocity versus voltage measurements to obtain the calibration factors listed in Table (1).

The three capacitance wave staffs were constructed by the author using the design of McGoldrick (1969). The 2-1/2 m gages consisted of a 1.0 cm diameter stripped coaxial cable mounted on a painted wooden frame as shown in Figure (2). The capacitance wave gage operates on the principal that a change of capacitor plate dimensions changes the circuitry voltage output. The insulated coaxial cable and the sea water act as the plates and the cable insulation as the dielectric. As the wave elevation changes, the capacitance of the circuit changes and the voltage output responds linearly.

The frame was rather heavily constructed and attached close to the tower to maintain a fairly rigid probe wire and to reduce water resistance on unattached parts. When assembled, the frame became somewhat unwieldy in the surf and created some resistance to flow around the support tower. The accuracy of the gages, however, was not believed effected. The electronic gear, including power source, was mounted in a waterproof brass container on top of the frame and two conductor cables carried the output signal shoreward.

The wave gages were calibrated in the laboratory to a depth of 1.7 m. Accuracy was estimated to be ± 0.005 m. The calibration plots are shown in Figure (1) and the results

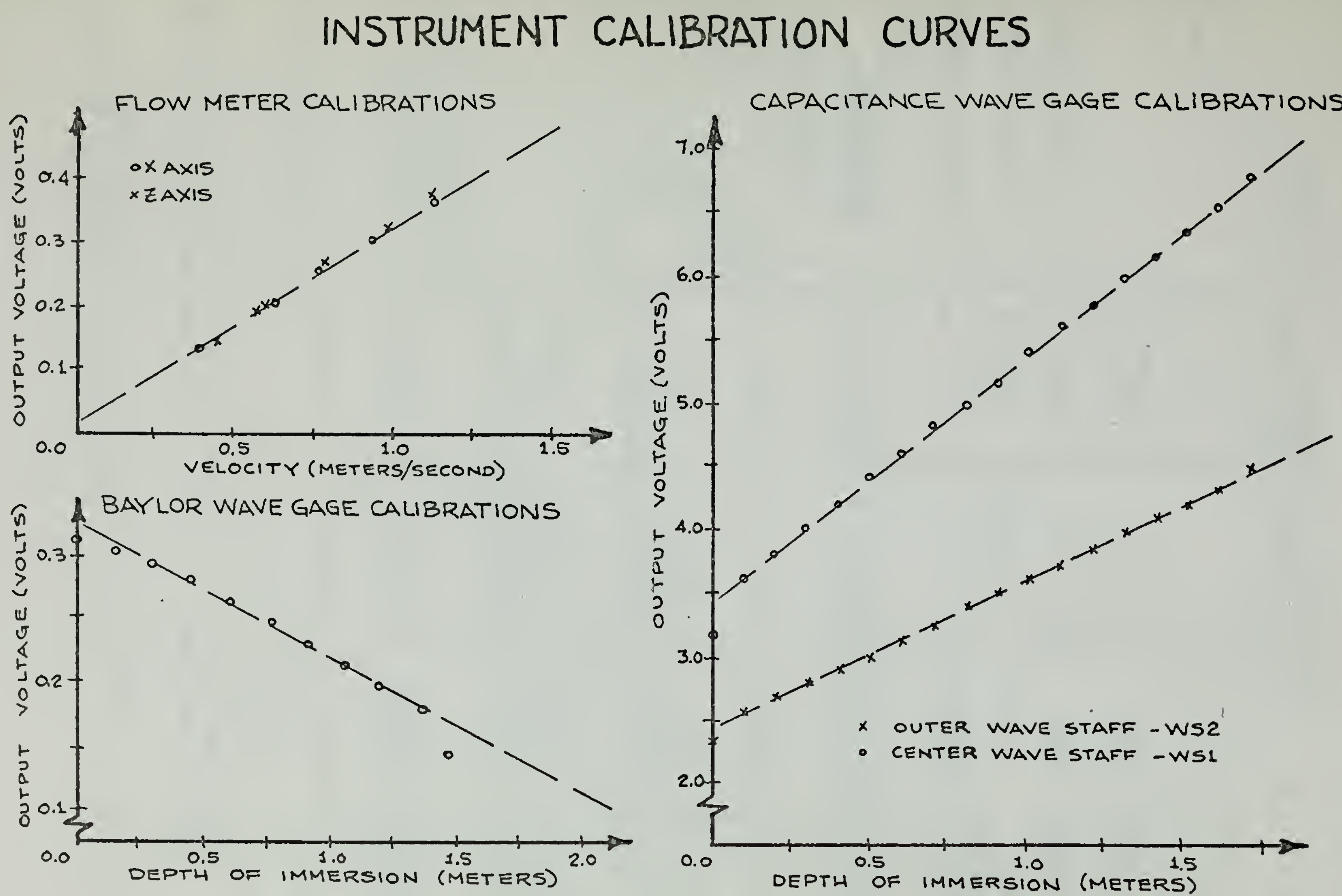

INSTRUMENT CALIBRATION CURVES
FLOW METER CALIBRATIONS
o X AXIS
x Z AXIS
OUTPUT VOLTAGE (VOLTS)
0.0
0.1
0.2
0.3
0.4
0.5
1.0
1.5
VELOCITY (METERS/SECOND)
BAYLOR WAVE GAGE CALIBRATIONS
OUTPUT VOLTAGE (VOLTS)
0.1
0.2
0.3
0.0
0.5
1.0
1.5
2.0
DEPTH OF IMMERSION (METERS)
CAPACITANCE WAVE GAGE CALIBRATIONS
OUTPUT VOLTAGE (VOLTS)
7.0
6.0
5.0
4.0
3.0
2.0
x OUTER WAVE STAFF - WS2
o CENTER WAVE STAFF - WS1
0.0
0.5
1.0
1.5
DEPTH OF IMMERSION (METERS)

Figure (1)

TABLE (1) - INSTRUMENT DESIGNATIONS AND CALIBRATION INFORMATION

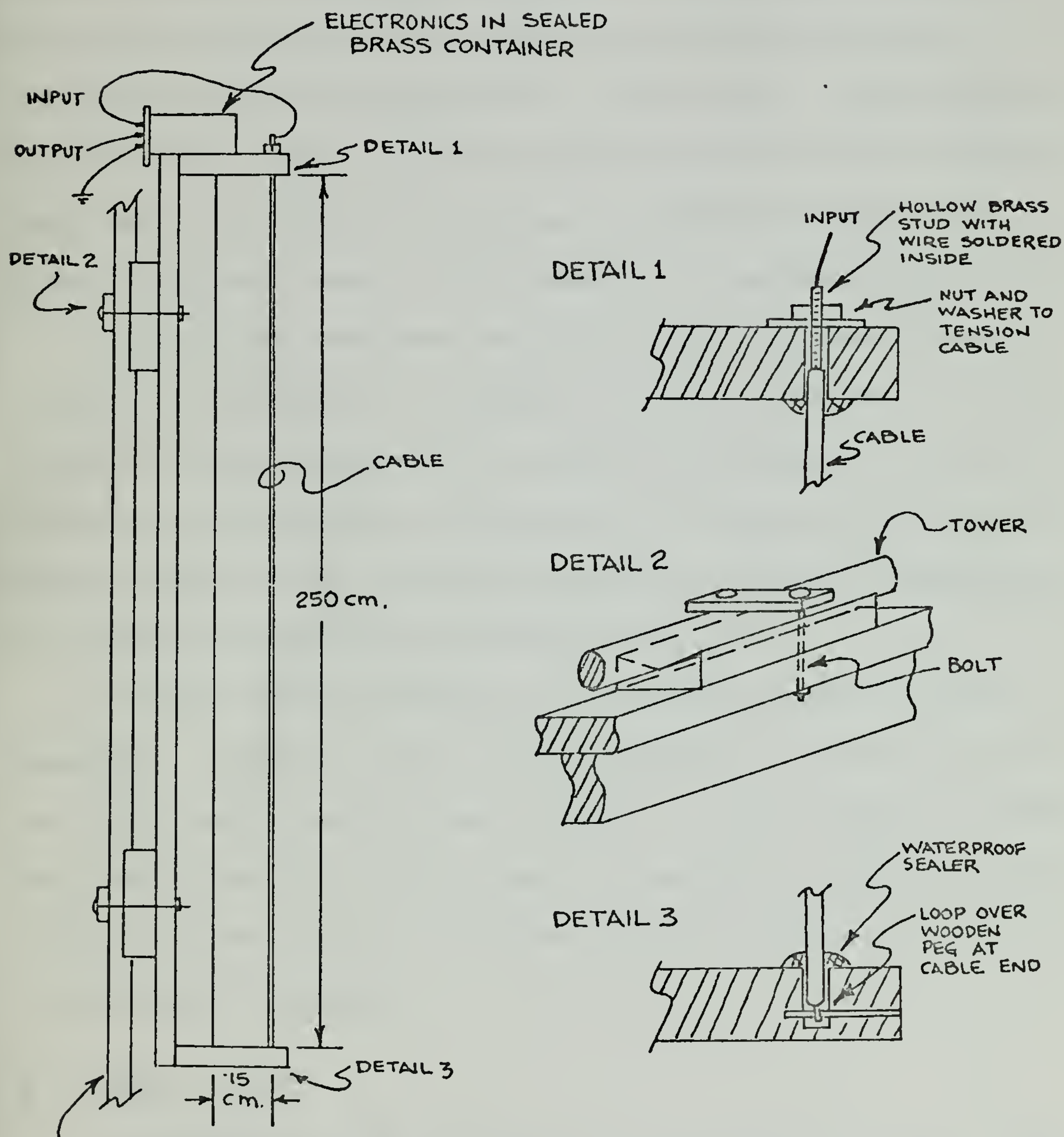
TRACK #	1	2	3	4/5
TITLE	Outer Profile	Center Profile	Inner Profile	Horiz/Vert Velocity
INSTRUMENT	WS2	WS1	BAY	FM1X/FM1Z
MANUFACTURER	Locally Made	Locally Made	Baylor	Marsh-McBirney
MODEL/SERIAL#	-	-	13528R	721/95
RANGES				
VOLTAGE OUT	3.40-8.29v	2.40-5.35v	0.33-0.16v	$\pm$1.0v
MEASUREMENT	0.0-2.5m	0.0-2.5m	0.0-1.52m	$\pm$3.05m/sec
HEIGHT ABOVE BOTTOM	0.74m	0.33m	0.24m	0.53m
LAB CALCULATIONS[1]				
MULT FACTOR	+0.511	+0.846	-9.405	+10.908
ADD FACTOR	-1.753	-2.029	+3.078	-0.223
STD. ERROR	$\pm$0.004m	$\pm$0.007m	$\pm$0.020m	$\pm$0.014m/sec
PROCESSING GAINS[2]				
A	x0.177	x0.236	x3.536	x1.414
B	x50	x50	x50	x100
C	x0.1131	x0.0848	x0.0057	x0.0071
FINAL CALIBRATION[3]				
MULT FACTOR	+0.058	+0.072	-0.053	+0.024
ADD FACTOR	-0.995	-1.699	+3.313	-0.068

[1] From linear regression of laboratory calibrations as shown in Figure (1).

[2] A - Instrument to analog tape, B - Analog tape, through filtering, to digital tape, and C - 1/(AxB), applied to digitally recorded voltage to compute instrument output.

[3] Factors applied to data in digital form (including instrument height) during computer analysis to obtain actual surface height and velocity values.

CAPACITANCE WAVE GAGE CONSTRUCTION



FRAME - REDWOOD (2X4") SEALED
WITH WATERPROOFING

CABLE - CENTER OF RG-11 COAXIAL
CABLE (APPROX. 1 CM OD)

Figure (2)

of a depth versus voltage output linear regression are shown in the calibration factors of Table (1).

The resistance wave gage was a Baylor Wave Measuring System Model #13528R with a 1.52 m wave height capacity. The gage consisted of two 1.27 cm stainless steel wire ropes mounted under tension on a tower and an electronics box located ashore. As the water level rose on the cables, they were shorted and a voltage was produced which was linearly proportional to the amount of exposed cable.

Calibration consisted of simply shorting the cables at various intervals and recording the output voltages. Calibration accuracy was ± 0.02 m when measurements were taken away from either end of the gage. The calibration plot is shown in Figure (1) and the calibration factors determined by linear regression are shown in Table (1).

All data was recorded on a 14 channel Sangamo Analog Recorder. Voltage inputs were reduced to a range of -1.0 to +1.0 v and recorded continuously. A strip chart recorder was used to monitor both input and recorder output voltages during the experiment. One wave profile data set (WS3) was lost during recording.

B. BEACH SET UP

The experiment was conducted at Del Monte Beach at the Naval Postgraduate School Beach Laboratory on Thursday, 23 May 1974. Data was recorded from 12:50 to 14:30 PM (PDT) (100 minutes). High tide was at 13:40 PM. The weather was

clear, with some gusty onshore wind (less than 10 knots) and no visible sea. The swell surf was mild with observed significant wave heights of between 0.5 and 0.75 m and periods of approximately 8 to 10 seconds. Breakers were predominantly spilling with an occasional plunging type. Refraction along the shore consistantly caused waves to break paralled to the beach.

The four towers used were steel pipes 6.3 cm in diameter and 3.6 m high with a 1.0 m diameter base. They were held up with 0.9 cm polypropylene rope tied to homemade screw-type anchors. A typical tower arrangement is shown in Figure (3). The towers were placed on a line perpendicular to the shore at specified distances. The towers remained visibly stable during measurements and it was felt that tower movement was not appreciable. The polypropylene lines had a tendancy to stretch and loosen and knots did not hold well. The use of steel guy wires would have reduced line slackness problems. The anchors were difficult to both install and remove and did not hold unless deeper than about 0.5 m. The experiment was concluded when Tower Two became unstable and fell as a knot failed. Flow meter number two (FM2) was mounted too high on the tower and was occasionally exposed, causing false readings. Thus this data could not be used for continuous analysis. Figure (4) is a diagram of the beach profile and the instrument arrangement.

TYPICAL TOWER ARRANGEMENT

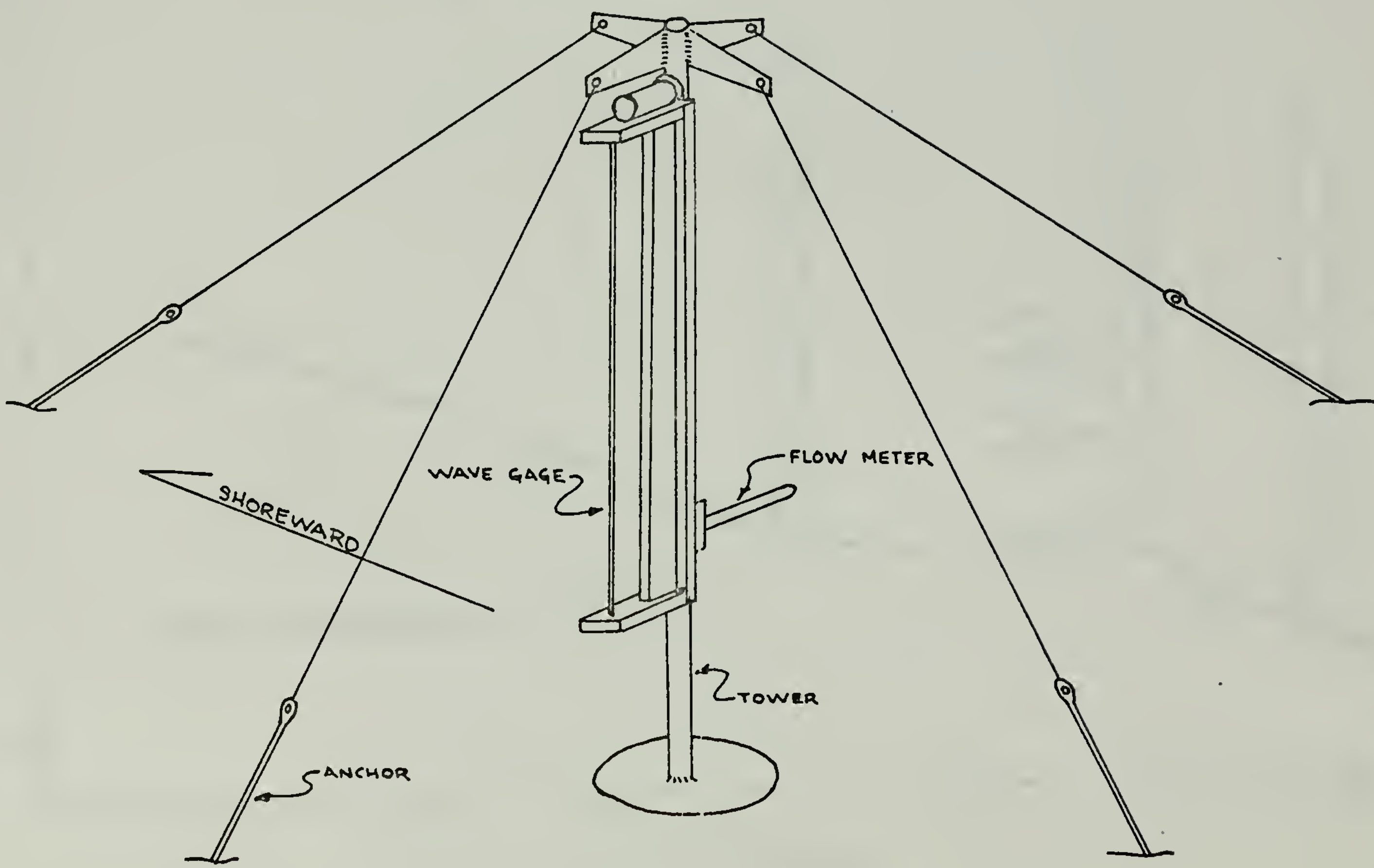


Figure (3)

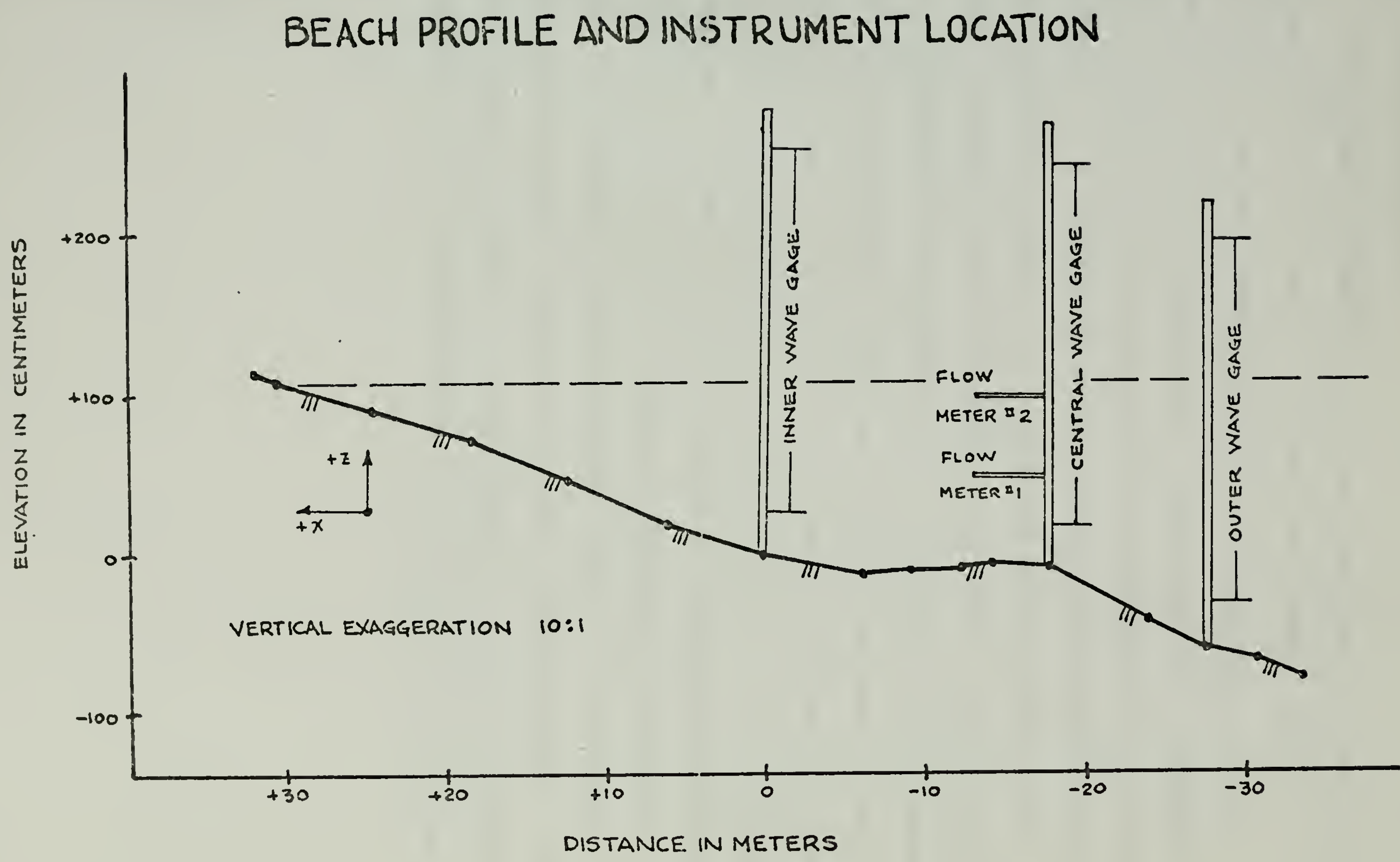

BEACH PROFILE AND INSTRUMENT LOCATION
ELEVATION IN CENTIMETERS
+200
+100
0
-100
INNER WAVE GAGE
CENTRAL WAVE GAGE
OUTER WAVE GAGE
FLOW
METER #2
FLOW
METER #1
+Z
+X
VERTICAL EXAGGERATION 10:1
+30
+20
+10
0
-10
-20
-30
DISTANCE IN METERS

Figure (4)

C. DATA PREPARATION

Data was recorded at the beach on eight channels at a speed of 1 7/8 in/sec. The data was played back at 7 1/2 in/sec and sampled at 100 Hz (1 sample per 0.01 seconds) or 25 Hz real time (1 sample per 0.04 seconds). The analog to digital conversion was performed on a CDC/9300 computer. A summary of tape recorder and digitization gains is included in Table (1). Playback data was amplified once, filtered, amplified again, digitized, and recorded. A matched set of Krohn-Heit filters with a cutoff frequency of 40 Hz (10 Hz real time) was used to low pass filter the analog signals. Filtering was conducted during this phase to reduce the possibility of 60Hz aliasing. The real time sampling interval was 0.04 seconds so the recorded Niquist frequency was 12.5 Hz. Digitized data was recorded on a nine track magnetic tape (labeled BUB191) in one file of 597 records, each record consisting of 2048 points or 256 data points for each of eight channels. Figure (5) gives examples of the recorded data taken during the experiment.

SAMPLES OF DATA AS RECORDED

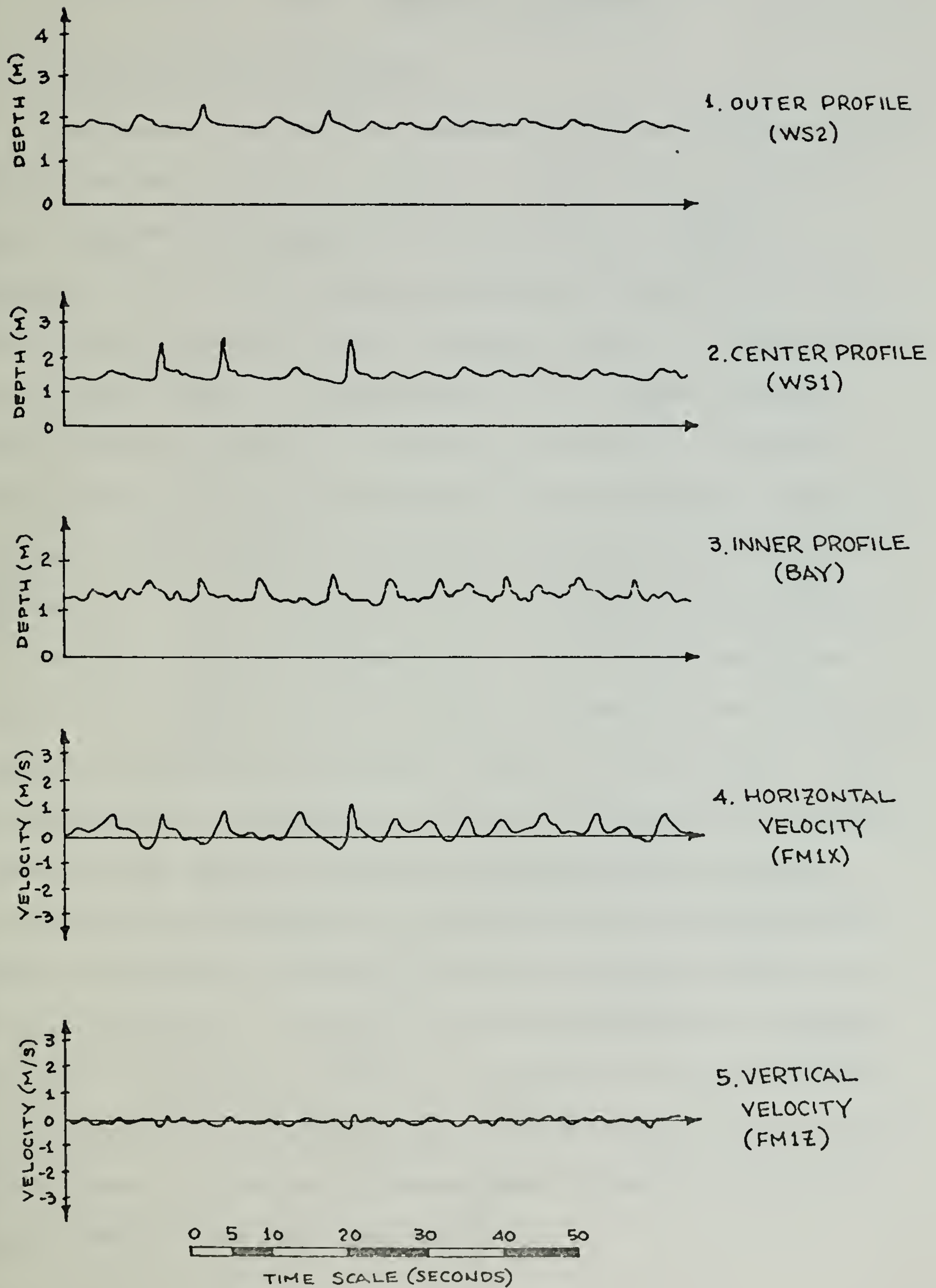


Figure (5)

III. SPECTRAL ANALYSIS

A. APPROACH TO DATA ANALYSIS

Continuous time series records of all measurements were taken for 100 minutes. A thirty minute sample record of each data set was spectrally analyzed on an IBM/360 computer. The power spectra generated described the composition of the data over a frequency range in terms of its mean square value. An examination of a power spectrum indicates the regions of greatest mean wave or velocity amplitude and their corresponding frequencies and will give a general relationship of energy concentrations across the frequency range. A comparison of two spectra by means of a cross-spectrum and subsequently a coherence and phase plot with frequency will indicate the regions and degree of linear relationship and phase between two data sets. Coherence can be thought of as the ratio between two measurements of the square of the gain factors for a constant parameter linear system. A coherence near 1.0 indicates that both spectra operate under the same gain factor or transform function, that is, their relationship is highly linear. A coherence near 0.0 indicates the two examined spectra are not related or are related only by a non-linear gain factor. Phase angle measurements indicate the time delay between two data set spectra.

The use of spectral analysis in the examination of data required the following assumptions be made:

1. The data was random. In other words, the data used represented one of many possible results that could have occured or was one physical realization of the random data process.

2. The random process was stationary. That is, the data set could be described in terms of certain average values which are true for all data sets of the same process.

3. The stationary random process was ergotic or all properties of the process for all time could be described by performing analysis on one finite data set.

Many processes found in nature can be treated as being ergotic, stationary, and random. The validity of this assumption as it applied to this experiment will be examined in Section (IV,C) of this paper.

B. COMPUTER ANALYSIS METHOD

A complete flow chart of data acquisition and analysis is presented in Figure (6) and is discussed briefly below. The equations used are given in Bendat and Piersol (1971). The parameters used for the spectral analysis process were chosen to balance the longest record which the computer could reasonably analyze with the best resolution over the frequency range of interest. The frequency band of 0.0 to 1.5 Hz was chosen to cover the region of gravity waves (0.033 to 1.0 Hz). Low pass filtering was used twice to

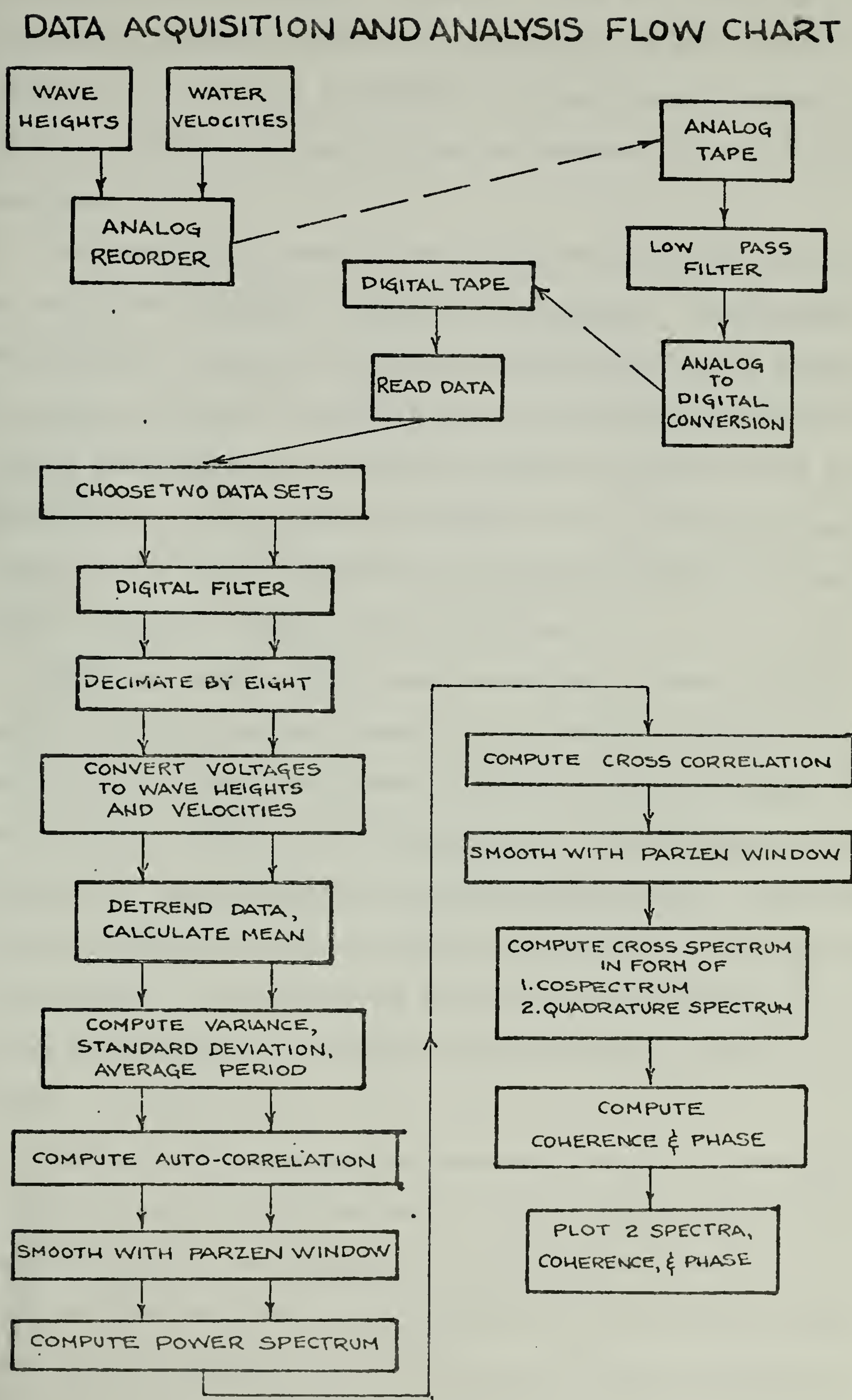

DATA ACQUISITION AND ANALYSIS FLOW CHART
WAVE HEIGHTS
WATER VELOCITIES
ANALOG RECORDER
ANALOG TAPE
LOW PASS FILTER
ANALOG TO DIGITAL CONVERSION
DIGITAL TAPE
READ DATA
CHOOSE TWO DATA SETS
DIGITAL FILTER
DECIMATE BY EIGHT
CONVERT VOLTAGES TO WAVE HEIGHTS AND VELOCITIES
DETREND DATA, CALCULATE MEAN
COMPUTE VARIANCE, STANDARD DEVIATION, AVERAGE PERIOD
COMPUTE AUTO-CORRELATION
SMOOTH WITH PARZEN WINDOW
COMPUTE POWER SPECTRUM
COMPUTE CROSS CORRELATION
SMOOTH WITH PARZEN WINDOW
COMPUTE CROSS SPECTRUM IN FORM OF
1. COSPECTRUM
2. QUADRATURE SPECTRUM
COMPUTE COHERENCE & PHASE
PLOT 2 SPECTRA, COHERENCE, & PHASE

Figure (6)

minimize 60 Hz aliasing. Folding of 60 Hz noise around the Niquist frequency would have appeared as peaks in the spectra at 0.625 and 0.9375 Hz. No such peaks showed up during analysis, demonstrating the success of the filtration employed.

The same 30 minutes of raw data was analyzed for each of the five channels. During each program, two channels were chosen, digitally filtered, and decimated by eight. The data was low pass filtered using a 25 weight filter with a cutoff frequency of 1.2 Hz and terminal frequency of 1.8 Hz. This filter, illustrated in Figure (7), is given in Davidson (1970). The final analyzed time step was thus 0.32 seconds with a Niquist frequency of 1.5625 Hz.

The data points were then converted to wave height and/or velocity values using the calibration factors of Table (1). A mean value was calculated for both data sets and the data was linearly detrended. The variance, standard deviation, and average period were calculated. The average period was determined by finding the time between zero axis upcrossings; the calculated average periods appear low using this method. The mean values for each data set are listed in Table (2).

For pairs of measured parameters, the auto-covariance functions were calculated using a five percent lag. Each auto-covariance was smoothed with a Parzen window. A Fourier transform was then applied to the smoothed auto-covariance functions and the two power density spectra

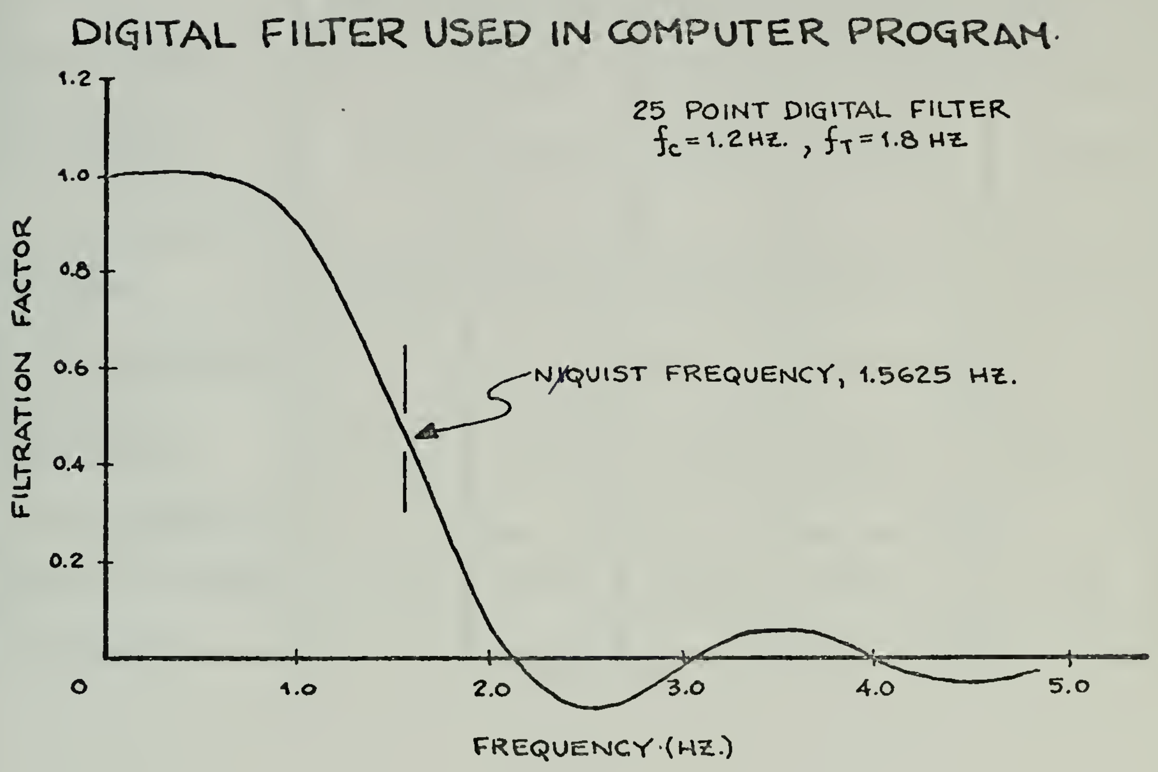

DIGITAL FILTER USED IN COMPUTER PROGRAM.
25 POINT DIGITAL FILTER
$f_c = 1.2$ HZ. , $f_T = 1.8$ HZ
NYQUIST FREQUENCY, 1.5625 HZ.
FILTRATION FACTOR
1.2
1.0
0.8
0.6
0.4
0.2
0
1.0
2.0
3.0
4.0
5.0
FREQUENCY (HZ.)

Figure (7)

TABLE (2) - STATISTICAL PARAMETERS

CALCULATED DURING ANALYSIS

TRACK	1	2	3	4	5
TITLE	OUTER PROFILE	CENTER PROFILE	INNER PROFILE	HORIZONTAL VELOCITY	VERTICAL VELOCITY
DESIGNATION	WS2	WS1	BAY	FM1X	FM1X
MEAN DEPTH OR VELOCITY (m or m/sec)	1.982	1.468	1.428	+0.018	+0.048
VARIANCE (m^2 or m^2/sec^2)	0.016	0.029	0.032	0.170	0.006
STANDARD DEVIATION (m or m/sec)	0.127	0.170	0.178	0.412	0.077
AVERAGE PERIOD (seconds)	5.53	5.29	4.20	6.20	3.10

determined. Bandwidth resolution for the spectra was 0.00544 Hz.

A cross-covariance function between data sets was then computed, smoothed with a Parzen window, a Fourier transform applied, and the cross-spectrum computed. The coherence and phase relations were calculated and the two spectra, the coherence, and the phase plotted.

IV. RESULTS

A. INTRODUCTION

The spectra generated were examined, the observed low frequency peaks were related to phenomenon which one would expect to find in the surf zone. The stationarity of the data sets was examined in order to determine the scope of applicability of the data.

An examination of theories which may be used in the surf zone was conducted using two approaches. First, measured velocity spectra were compared with velocity spectra calculated from the center surface profile using a linear wave theory transfer function. Solitary wave theory was then to be used to develop a discrete line spectrum for a similar type of comparison. However, the results showed that: (1) the linear theory transfer function calculated horizontal velocity very well and (2) there were no identifiable harmonics in the measured spectra which could be related to such a discrete spectrum; this indicated that solitary wave theory was not applicable under the experiment conditions.

A second approach to the examination of applicable wave theories was to compare measured values of celerity or wave phase speed with theoretical values.

B. EXAMINATION OF LOW FREQUENCY SPECTRAL COMPONENTS

Figures (8) and (9) give the results of the spectral analysis when comparing the outer and center profiles and the center and inner profiles. Figure (10) is a spectral comparison between horizontal and vertical measured velocity spectra. Figure (11) is a superposition of the three surface profile spectra. Table (3) is a summary of low frequency spectral peaks found throughout the five spectra generated and gives a wave height or velocity value for each peak relative to a maximum spectral peak of 1.0. These values are presented in this manner for comparison purposes only.

The following observations can be made concerning the results shown in the Figures and Table (3):

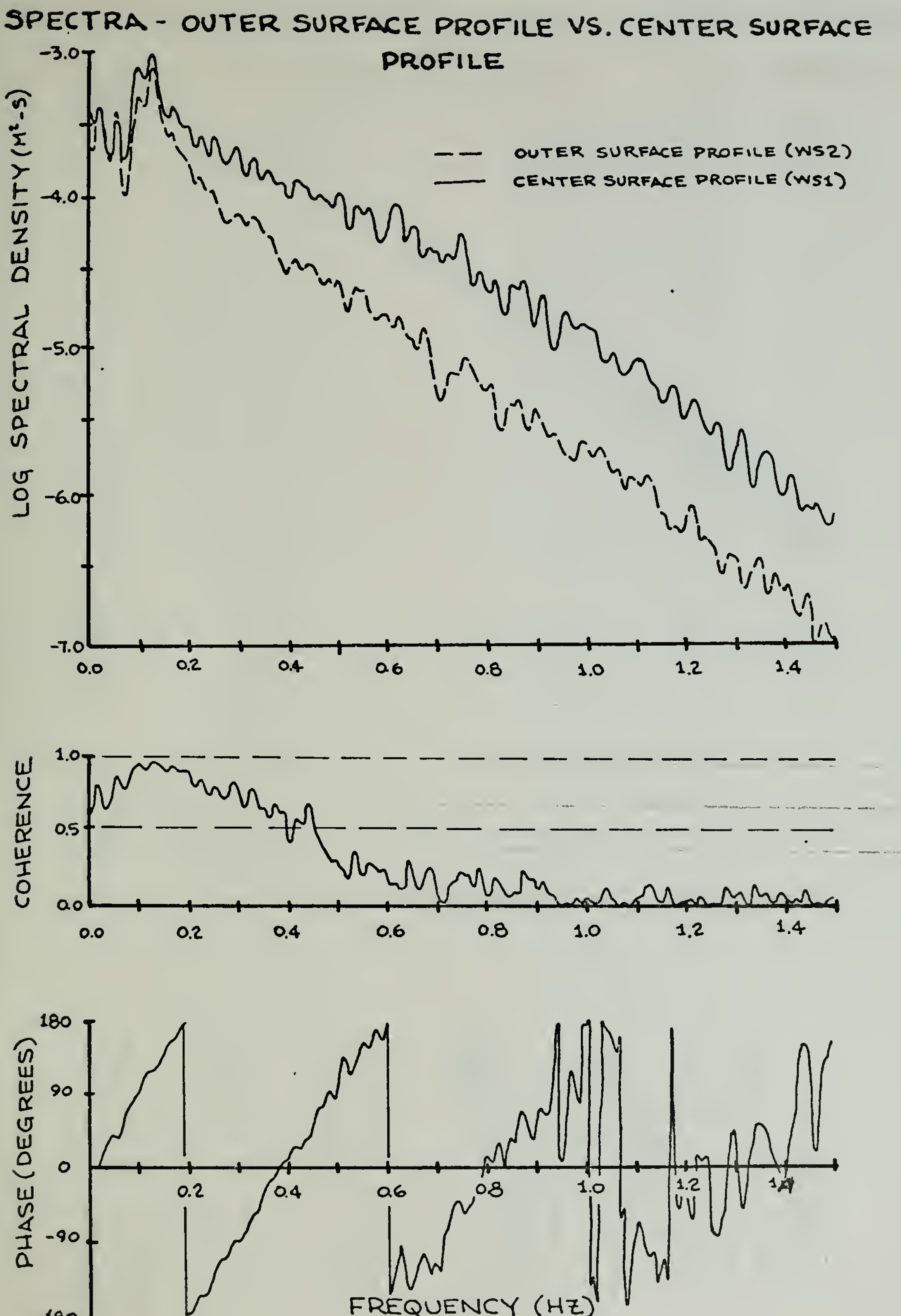
1. The maximum wave energy for all spectra is concentrated at a primary frequency of 0.125 Hz corresponding to a period of 8.0 seconds.

2. A secondary peak exists at 0.098 Hz (10.2 seconds).

3. An approximate subharmonic of the primary frequency exists at 0.060 Hz (16.7 seconds).

4. A fourth peak of interest shows up at 0.011 Hz (92 seconds) on the inner profile and vertical velocity spectra.

5. A major peak on the horizontal velocity spectrum only exists at 0.016 Hz (61.2 seconds).



SPECTRA - OUTER SURFACE PROFILE VS. CENTER SURFACE PROFILE
LOG SPECTRAL DENSITY (M²-S)
-3.0
-4.0
-5.0
-6.0
-7.0
OUTER SURFACE PROFILE (WS2)
CENTER SURFACE PROFILE (WS1)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
COHERENCE
1.0
0.5
0.0
PHASE (DEGREES)
180
90
0
-90
-180
FREQUENCY (HZ)

Figure (8)

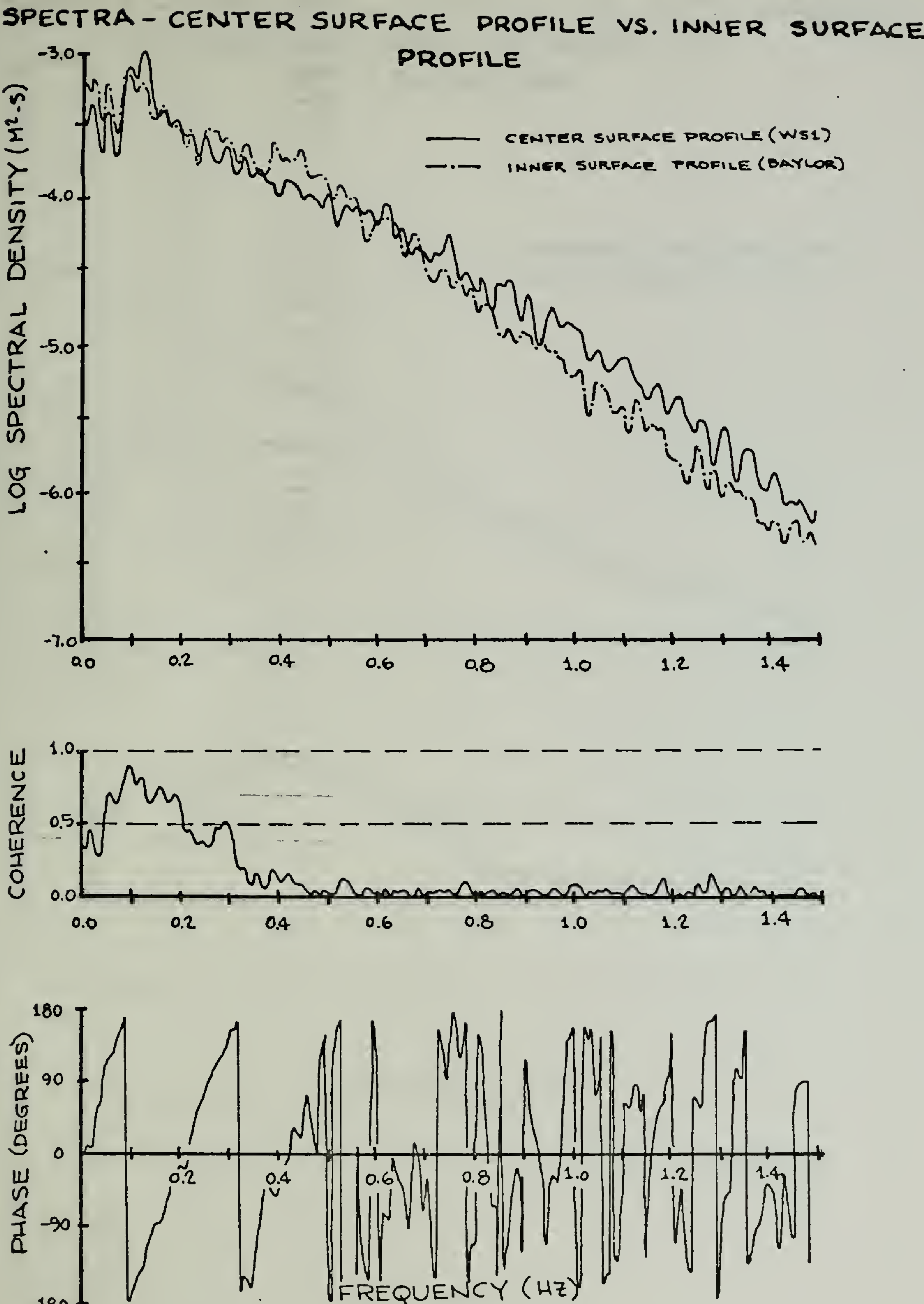

SPECTRA - CENTER SURFACE PROFILE VS. INNER SURFACE PROFILE
LOG SPECTRAL DENSITY (M²-s)
CENTER SURFACE PROFILE (WS1)
INNER SURFACE PROFILE (BAYLOR)
-3.0
-4.0
-5.0
-6.0
-7.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
COHERENCE
1.0
0.5
0.0
PHASE (DEGREES)
180
90
0
-90
-180
FREQUENCY (HZ)

Figure (9)

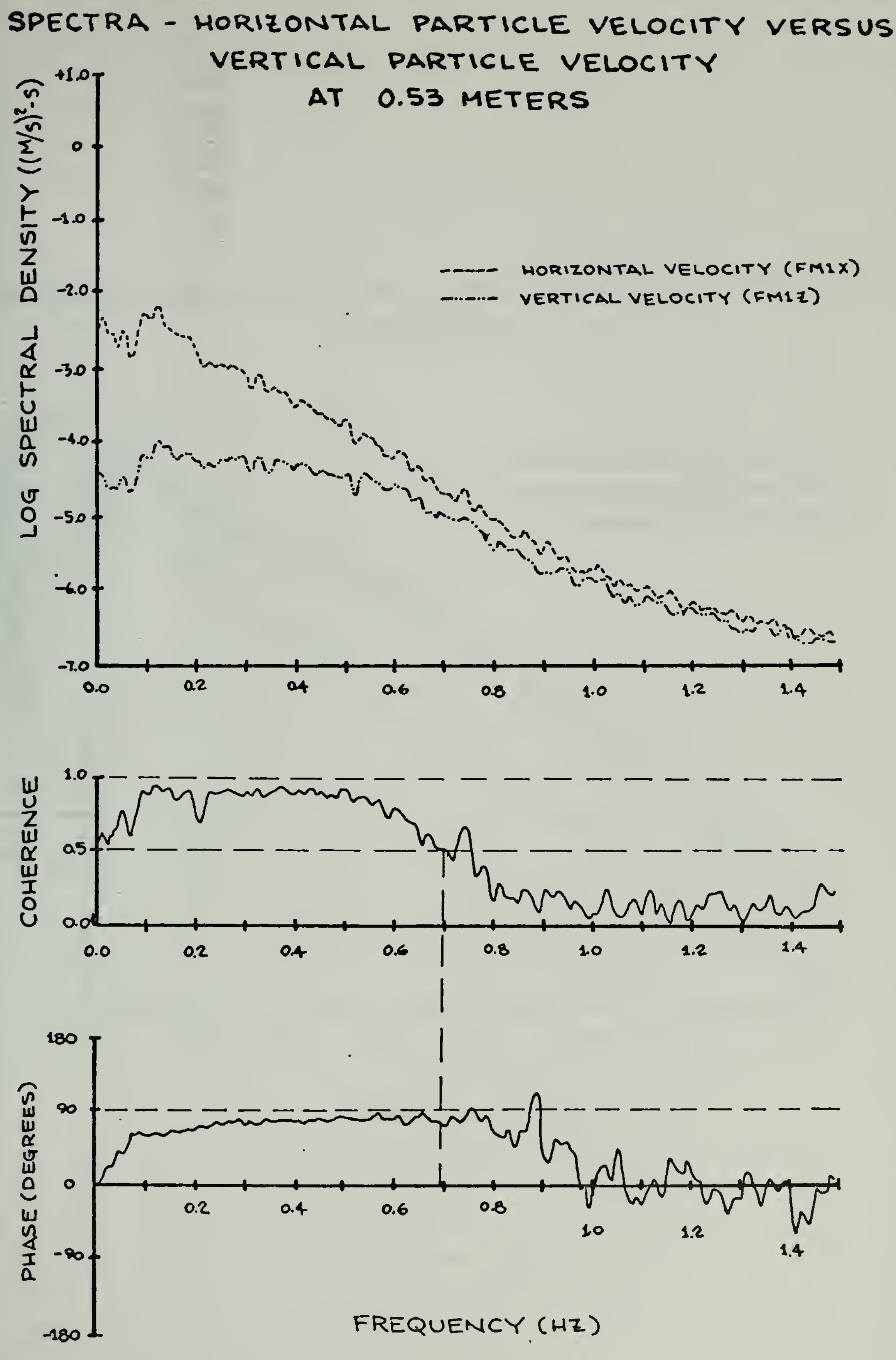

SPECTRA - HORIZONTAL PARTICLE VELOCITY VERSUS
VERTICAL PARTICLE VELOCITY
AT 0.53 METERS
LOG SPECTRAL DENSITY ((M/s)^2-s)
+1.0
0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
HORIZONTAL VELOCITY (FM1X)
VERTICAL VELOCITY (FM1Z)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
COHERENCE
1.0
0.5
0.0
PHASE (DEGREES)
180
90
0
-90
-180
FREQUENCY (HZ)

Figure (10)

SUPERPOSITION OF THE THREE SURFACE PROFILE SPECTRA

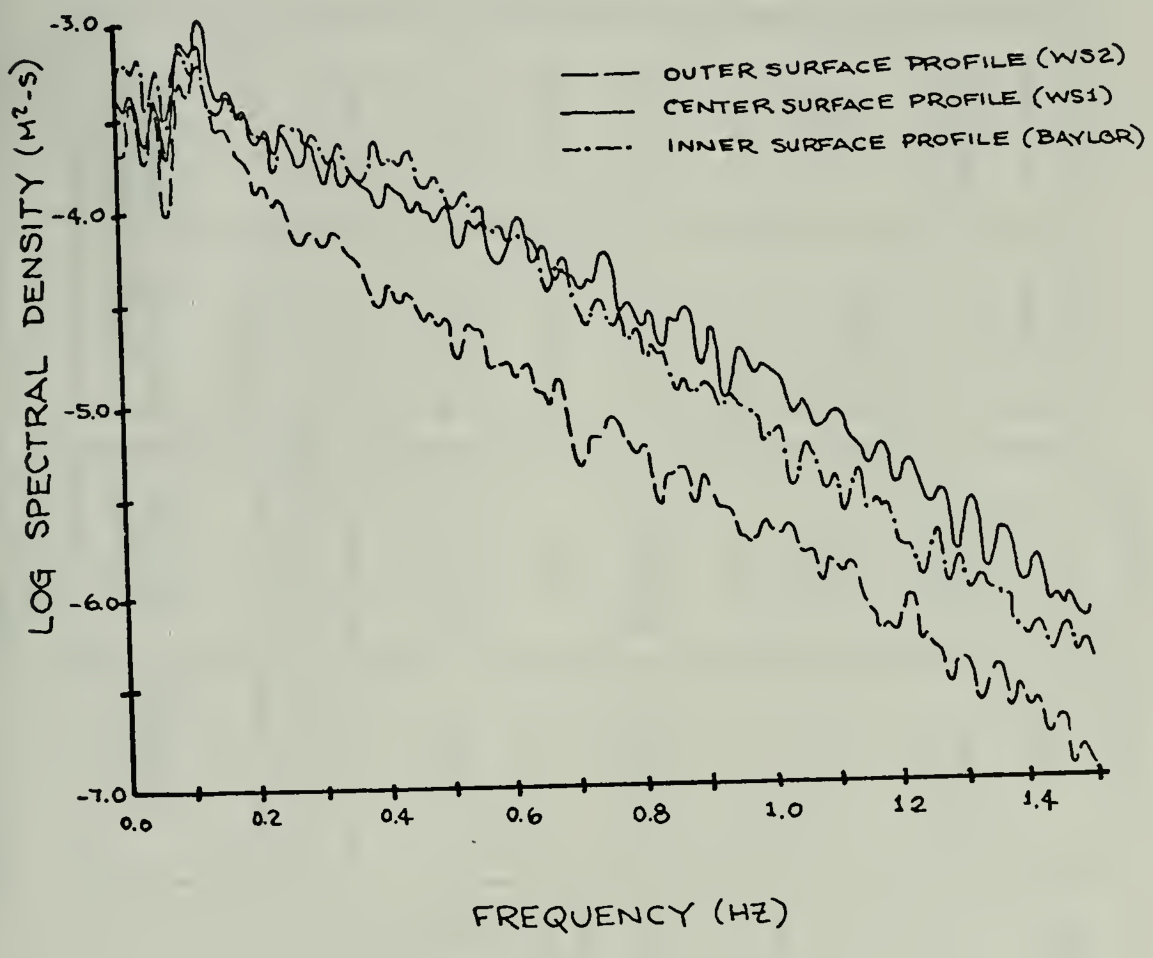


Figure (11)

TABLE (3) - SUMMARY OF LOW FREQUENCY SPECTRAL PEAKS

TITLE PEAKS NOTED*	OUTER PROFILE h(f)/hmax	CENTER PROFILE h(f)/hmax	INNER PROFILE h(f)/hmax	HORIZONTAL VELOCITY V(f)/Vmax	VERTICAL VELOCITY V(f)/Vmax
A. f=0.011 Hz T=92. sec	No peak	No peak	0.92	No peak	0.64
B. f=0.016 Hz T=61.2 sec	No peak	No peak	No peak	0.85	No peak
C. f=0.022 Hz T=45.9 sec	0.74	0.66	No peak	No peak	No peak
D. f=0.027 Hz T=36.7 sec	No peak	No peak	0.93	No peak	No peak
E. f=0.060 Hz T=16.7 sec	0.65	0.62	0.88	0.66	0.57
F. f=0.098 Hz T=10.3 sec	0.80	0.90	1.00 MAXIMUM	0.89	0.78
G. f=0.125 Hz T=8.0 sec	1.00 MAXIMUM	1.00 MAXIMUM	0.90	1.00 MAXIMUM	No peak
H. f=0.131 Hz T=7.6 sec	No peak	No peak	No peak	No peak	1.00 MAXIMUM

*In order of increasing frequency.

6. From a qualitative examination of the high frequency ends of the three profile spectra (Figure (11)), it appears that turbulence increases to a peak at the breakers and the waves seem to reorganize slightly inside this point.

Without further data analysis, discussion of these observations can be made only in a general sense. The observation of a primary frequency at 0.125 Hz agrees well with the wave periods of eight to ten seconds observed during the beach experiment. The additional peak at 0.098 Hz indicates that incoming waves were probably composed of a combination of 8.0 and 10.2 second waves.

Guzza and Davis (1974) state that in a theoretical analysis of edge waves excited by incoming waves, the prominent edge wave mode is the first subharmonic of the primary frequency. An energy peak was observed at this frequency. The author feels that the peak at 0.011 Hz, which shows on the inner profile and vertical velocity spectra only, may also be caused by an edge wave in the swash zone. Further experiments with profile measurements in a line parallel to the beach will clarify edge wave observations.

The comment that the turbulence inside the breaker zone decreases must be tempered by the fact that the inner wave gage was not the same type as the other two gages. It is felt that the Baylor wave gage was not as responsive to high frequencies as were the capacitance wave gages. Future studies with matched gages across the entire surf zone will clarify this question of wave organization.

C. EXAMINATION OF STATIONARITY

As the tide rises and the mean water depth increases, the breaker zone should move shoreward, and the mean parameters measured (mean depth and variance) at the towers should change. This series of events would result in a non-stationary situation. In Section (III.A) it was stated that if the data were ergotic, the measurements taken and analyzed during this experiment were typical of all waves in the breaker zone. This rather bold assumption can be examined by checking for stationarity of the data over the period of measurements.

The data is assumed to be weakly stationary if the mean and mean square values calculated are constant with time or if the auto-correlation function or its Fourier transform, the energy density spectrum, is constant for adjacent lengths of records. Both approaches were taken to verify stationarity. Energy density spectra were computed for the outer and center profiles during two independent 30 minute time segments and are illustrated in Figure (12). In a general sense (examining slopes and energy peaks), they compare favorably.

Mean depths and variances were then calculated for ten overlapping samples of 30 minutes each and are plotted in Figure (13). A non-parametric run test was applied to the data as described by Bendat and Piersol (1971) to check for stationarity. On the basis of this test, the data did not qualify as stationary.

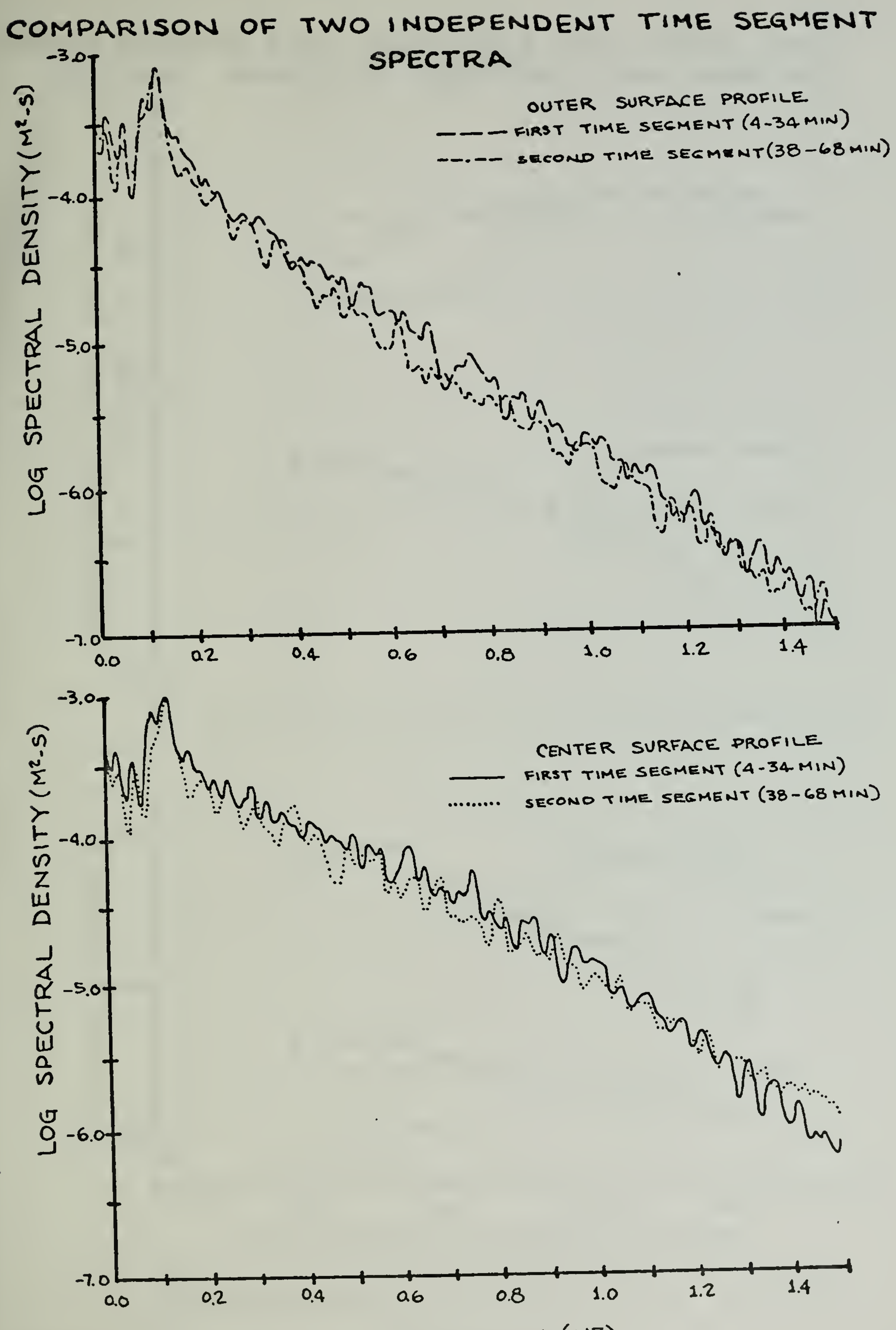
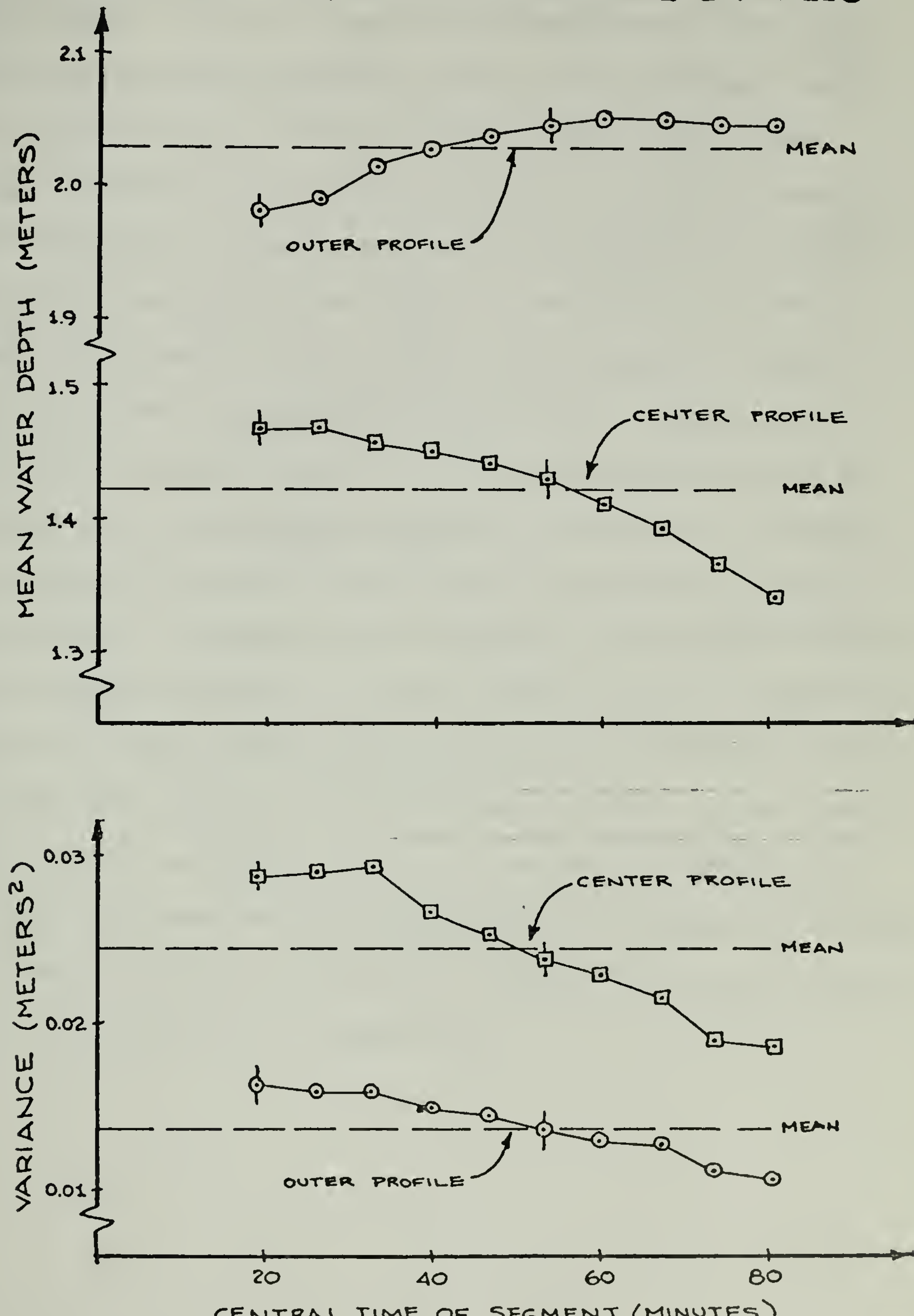

COMPARISON OF TWO INDEPENDENT TIME SEGMENT SPECTRA
OUTER SURFACE PROFILE
FIRST TIME SEGMENT (4-34 MIN)
SECOND TIME SEGMENT (38-68 MIN)
LOG SPECTRAL DENSITY (M^2-S)
-3.0
-4.0
-5.0
-6.0
-7.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
CENTER SURFACE PROFILE
FIRST TIME SEGMENT (4-34 MIN)
SECOND TIME SEGMENT (38-68 MIN)
LOG SPECTRAL DENSITY (M^2-S)
-3.0
-4.0
-5.0
-6.0
-7.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
FREQUENCY (HZ)

Figure (12)

MEAN DEPTHS AND VARIANCES OF OUTER AND CENTER PROFILES FOR TEN TIME SAMPLES



ϕ⌽ INDICATES SEGMENT FOR WHICH SPECTRUM COMPUTED.

Figure (13)

The non-stationarity can be explained by a number of observations. First, it must be re-emphasized that the waves measured were unusually small and consistantly of the spilling type. The bottom hump shown in the beach profile (Figure (4)) at -18 m appeared to trip the breakers in the vicinity of the center wave gage despite an apparent increase in the still water depth. The height of waves outside the breaker point, which can be related to the variance of the outer profile measurements, decreased as the depth increased with time. This was an indication of a decrease in the shoaling effect on the waves. Set down, the difference between still water level and mean depth at the breakers, increased as the breaker wave height decreased at the center wave gage. Future analysis should concentrate on this set down effect and its relation to set down theory.

Thus, the rising of the tide was the main factor contributing to the non-stationarity of the data. Despite the fact that the data was non-stationary, the analysis was still valid when the fact that the data applies to a very special set of circumstances is considered.

D. LINEAR THEORY APPLICATIONS

Airy or linear wave theory assumes that the surface profile is sinusoidal, i.e.,

$$\eta(t) = A \cos(\sigma t) \tag{1}$$

Linear theory horizontal and vertical water particle velocities at the depth z (z positive upward) below the mean water level are given by

$$u(t) = A\sigma \frac{\cosh(k(h+z))}{\sinh(kh)} \cos(\sigma t) \tag{2}$$

and

$$w(t) = A\sigma \frac{\sinh(k(h+z))}{\sinh(kh)} \sin(\sigma t) \tag{3}$$

Horizontal and vertical velocity spectra can be computed from the wave spectrum using the equations

$$S_{uc}(f) = \left[\frac{\cosh(k(h+z))}{\sinh(kh)}\right]^2 S_\eta(f) \tag{4}$$

and

$$S_{wc}(f) = \left[\frac{\sinh(k(h+z))}{\sinh(kh)}\right]^2 S_\eta(f) \tag{5}$$

The wave number, k, was calculated using an iteration of the linear theory characteristic equation

$$\sigma^2 = gk \tanh(kh) \tag{6}$$

Calculated horizontal (S_{uc}) and vertical (S_{wc}) velocity spectra were computed using the center surface profile spectrum and compared with measured spectra (S_{um} and S_{wm}) as shown in Figures (14) and (15). The calculated and measured horizontal velocity spectra, S_{uc} and S_{um}, (Figure (14)) compare well, indicating that linear wave theory was applicable for this experiment. On the other hand, the calculated and measured vertical velocity spectra (S_{wc} and S_{wm}), shown in Figure (15) did not agree well at all. The lack of agreement between these vertical velocity spectral magnitudes could be partially attributed to a low signal to noise ratio in the measurements (note the vertical velocity time sample relative to horizontal velocity time sample in Figure (5) which greatly reduced the accuracy of the measured velocity spectrum.

Phase measurements are used to substantiate the findings that linear theory was applicable. Equations (1) and (2) show that the center surface profile and horizontal velocity measurements should have been in phase (both have cos (σt) terms). An approximately zero degree phase was observed well beyond the 0.5 coherence point (Figure (14)). The cos (σt) and sin (σt) terms of equations (1) and (3) indicate that the surface profile and vertical velocity measurements should be 90 degrees out of phase. Figure (15) illustrates that this phase difference was observed in a range up to the 0.5 coherence.

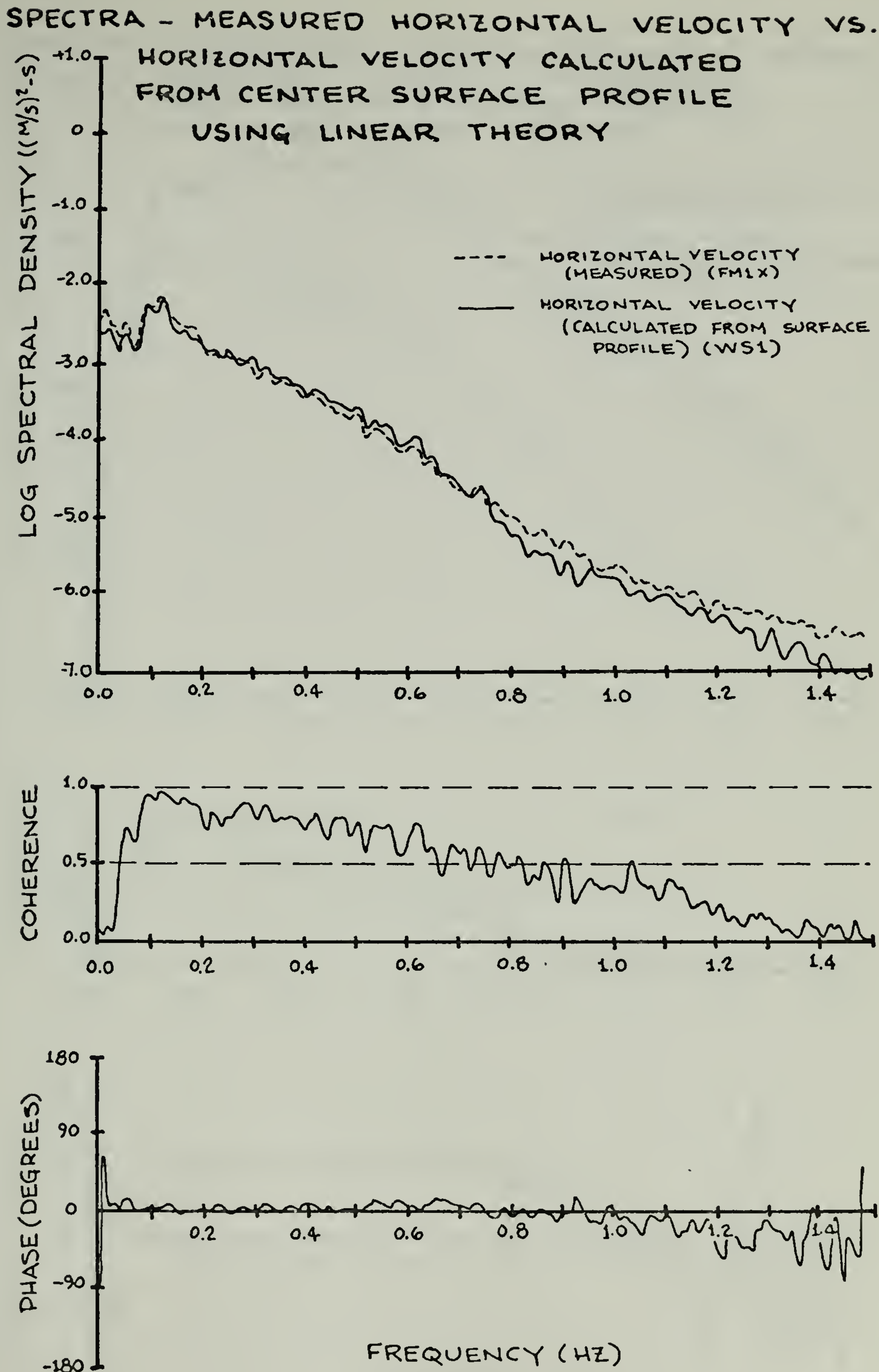
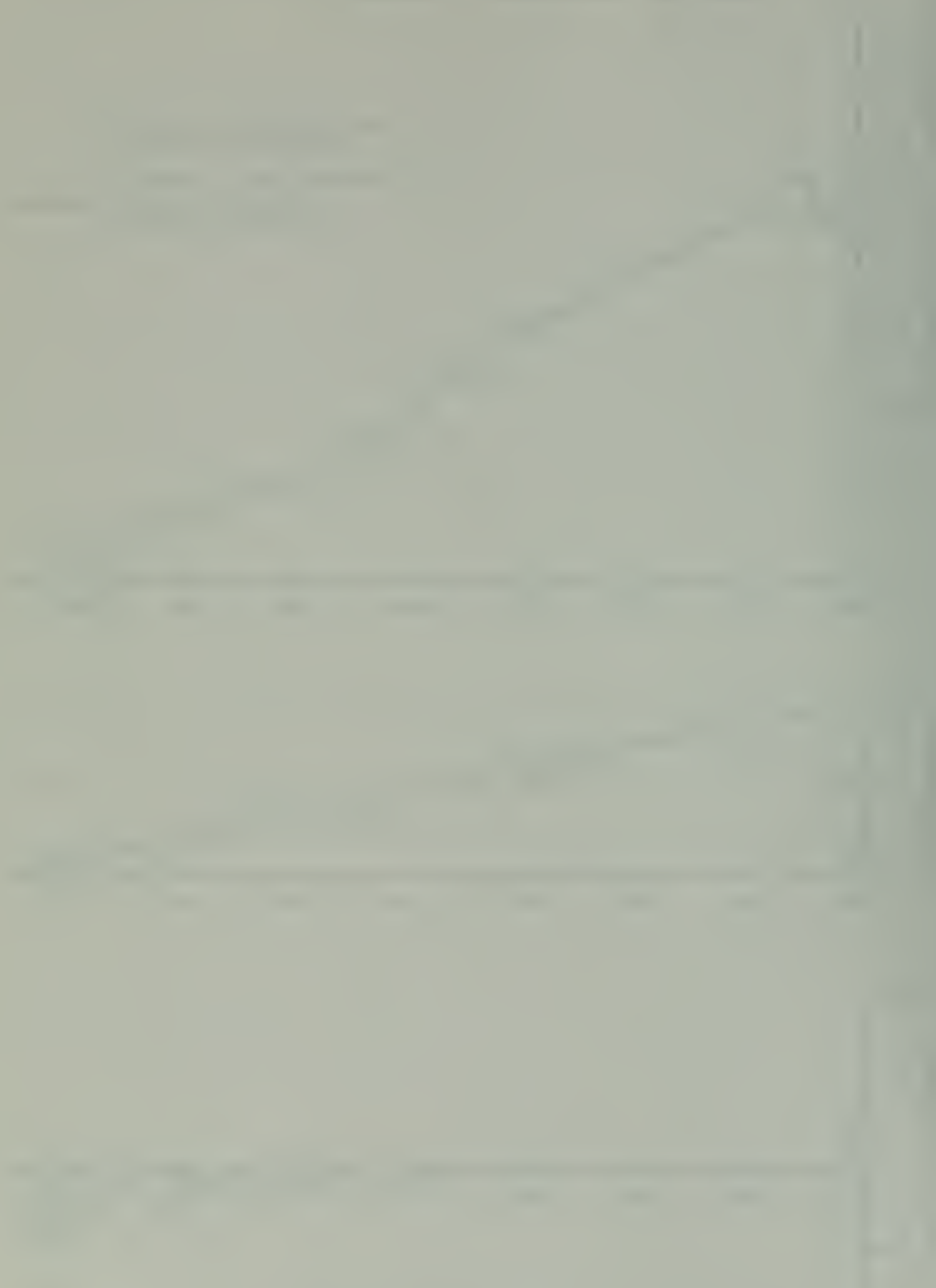

SPECTRA - MEASURED HORIZONTAL VELOCITY VS. HORIZONTAL VELOCITY CALCULATED FROM CENTER SURFACE PROFILE USING LINEAR THEORY
LOG SPECTRAL DENSITY ((M/S)²-S)
+1.0
0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
HORIZONTAL VELOCITY (MEASURED) (FM1X)
HORIZONTAL VELOCITY (CALCULATED FROM SURFACE PROFILE) (WS1)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
COHERENCE
1.0
0.5
0.0
PHASE (DEGREES)
180
90
0
-90
-180
FREQUENCY (HZ)

Figure (14)



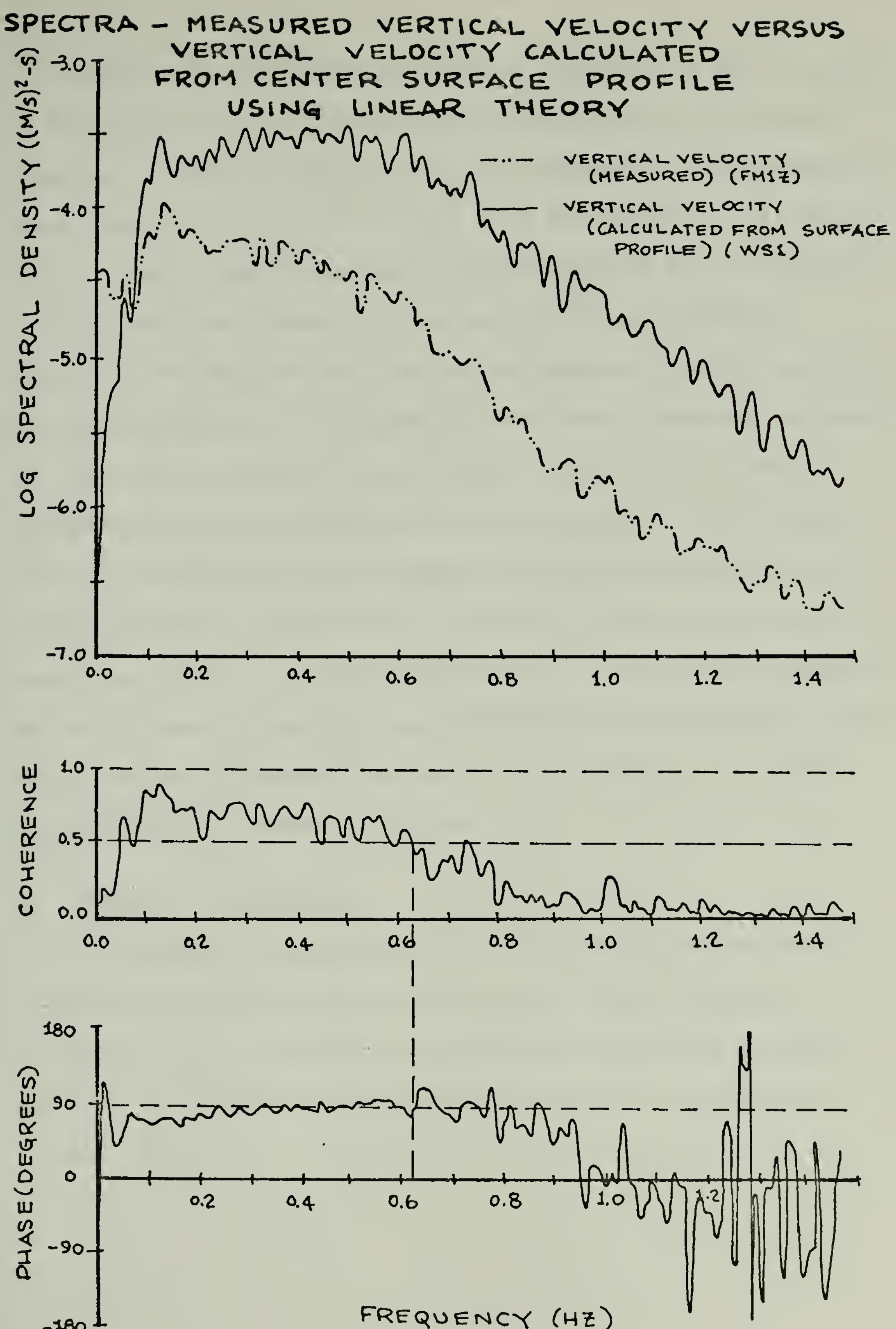

SPECTRA - MEASURED VERTICAL VELOCITY VERSUS VERTICAL VELOCITY CALCULATED FROM CENTER SURFACE PROFILE USING LINEAR THEORY
LOG SPECTRAL DENSITY ((M/S)²-S)
-3.0
-4.0
-5.0
-6.0
-7.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
VERTICAL VELOCITY (MEASURED) (FM1Z)
VERTICAL VELOCITY (CALCULATED FROM SURFACE PROFILE) (WS1)
COHERENCE
1.0
0.5
0.0
PHASE (DEGREES)
180
90
0
-90
-180
FREQUENCY (HZ)

Figure (15)

Finally, a high coherence would indicate a high degree of linearity in the transfer functions between different spectra. Coherence above 0.5 was observed for an approximate frequency range of 0.0 to 0.65 Hz (Figures (14) and (15)). This high value again substantiated the excellent results obtained when a linear wave theory transfer function was applied to the center surface profile spectrum when calculating the horizontal velocity. Whereas coherence is high for the same range, linear wave theory grossly overpredicts the vertical velocity spectrum. The author is led to believe that a linear relationship between the surface profile and vertical velocity exists but is not predicted well by linear wave theory. A further indication of the linearity between measurements was noted due to the high coherence between horizontal and vertical velocity measurements as shown in Figure (10).

E. CELERITY COMPARISONS

A summary of the various celerity calculations made in this section is included in Table (4). The measured celerity, C_1, is computed considering the shift in phase existing between two adjacent wave gages as plotted in Figure (16).

TABLE (4) - SUMMARY OF CELERITY CALCULATIONS

TRACK / DESIGNATION	1 Outer Profile	Average 1 & 2	2 Center Profile	Average 2 & 3	3 Inner Profile
$C_1 = \frac{\sigma}{\phi} x$ MEASURED NON-DISPERSIVE	-	3.95	-	3.78	-
$C_2 = (gh)^{1/2}$ LINEAR THEORY	4.40	4.10	3.80	3.77	3.74
$C_3 = (g(h+H_s))^{1/2}$ SOLITARY WAVE OR CNOIDAL THEORY	4.93	4.76	4.59	4.58	4.58
$C_4(f)$ at f=.125 DISPERSIVE	-	4.04	-	3.70	-

All units are in m/sec.

At $x_1 = 0$, let

$$\eta_1 = A_1 \cos(-\sigma t) \tag{7}$$

Then at $x_2 = x$

$$\eta_2 = A_2 \cos(kx-\sigma t) \tag{8}$$

Therefore, the phase shift, ϕ, between stations 1 and 2 becomes

$$\phi = k(f)\, x \tag{9}$$

By definition

$$C(f) = \frac{\sigma(f)}{k(f)} \tag{10}$$

Or substituting and solving for $C_1(f)$

$$C_1(f) = \frac{\sigma(f)}{\phi(f)}\, x \tag{11}$$

The dotted lines in Figure (16) plot a constant change in phase with frequency over the coherent ranges of Figures (8) and (9). This surprising result indicates that wave celerity in the surf zone did not depend on frequency, that is, the waves were non-dispersive.

The celerity was then computed for points between stations using the linear theory approximation for shallow water waves

$$C_2 = (gh)^{1/2} = \text{constant} \tag{12}$$

These values agree well with the measured celerity, C_1 ($\pm$ 4 percent). Again, as stated in the previous section, it appears linear theory is applicable in the surf zone.

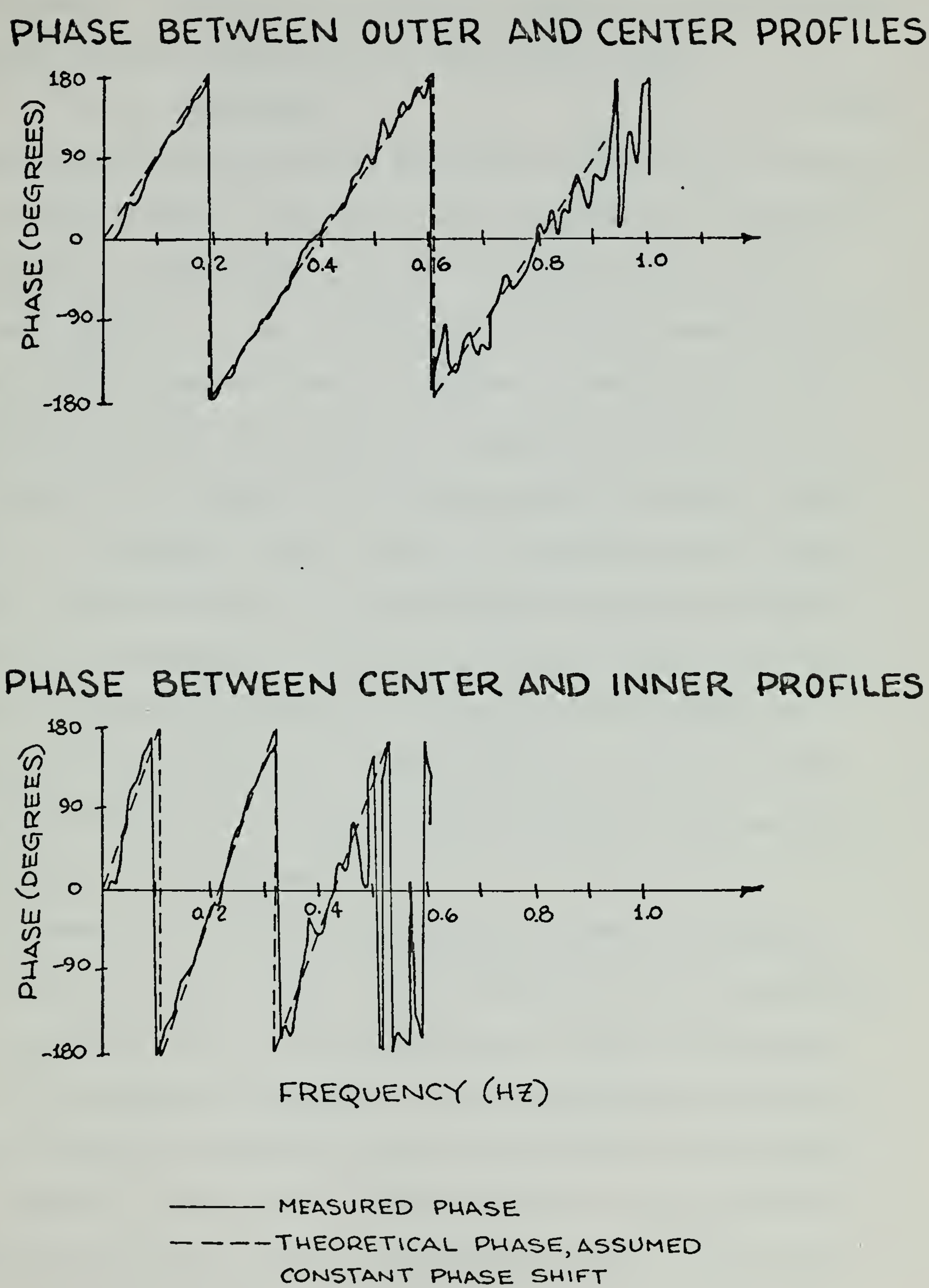

PHASE BETWEEN OUTER AND CENTER PROFILES
PHASE (DEGREES)
180
90
0
-90
-180
0.2
0.4
0.6
0.8
1.0
PHASE BETWEEN CENTER AND INNER PROFILES
PHASE (DEGREES)
180
90
0
-90
-180
0.2
0.4
0.6
0.8
1.0
FREQUENCY (HZ)
MEASURED PHASE
THEORETICAL PHASE, ASSUMED CONSTANT PHASE SHIFT

Figure (16)

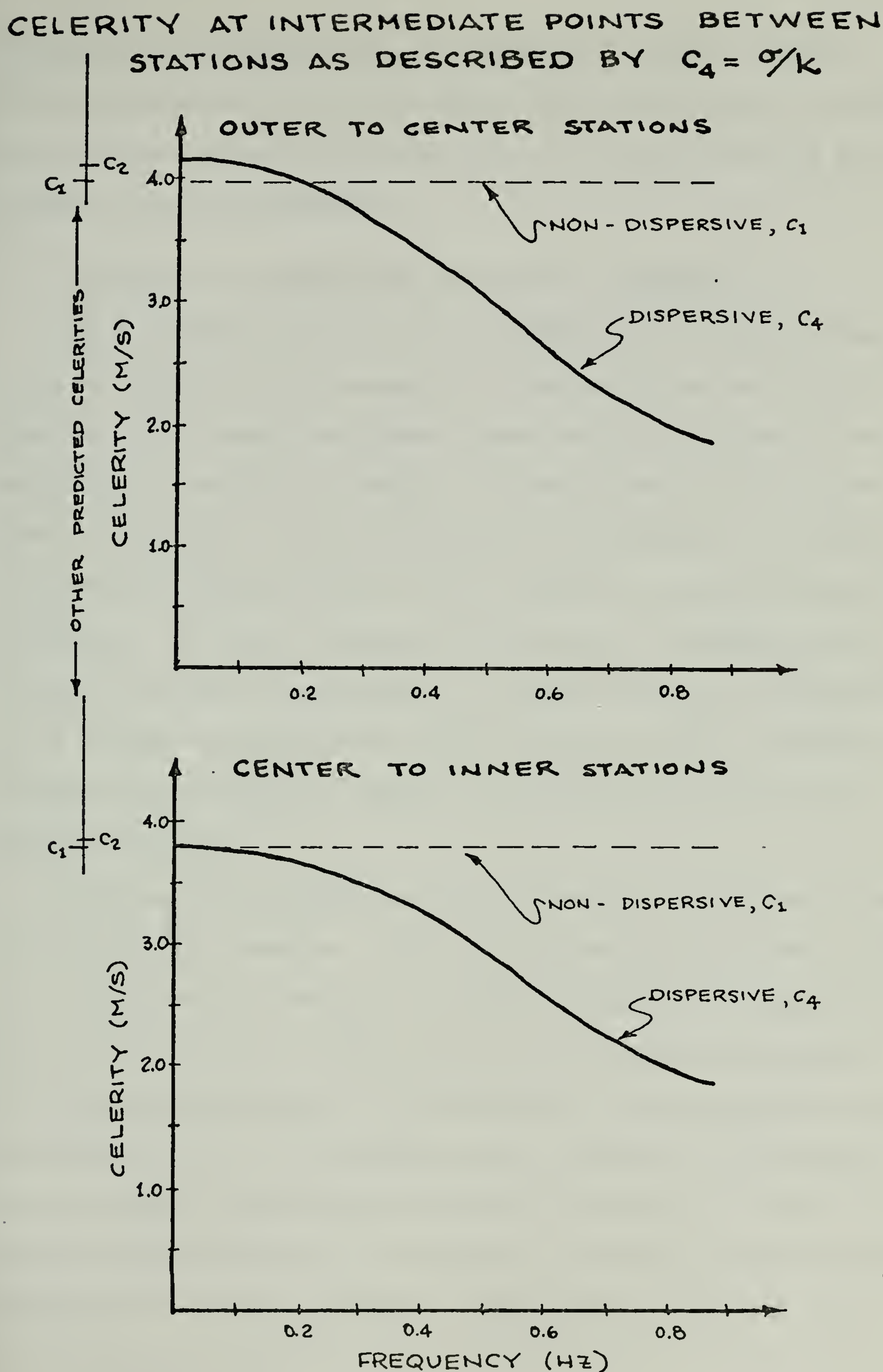
Using the significant wave height, H_s, calculated from the variance, celerity was computed using the approximation for both cnoidal theory and solitary wave theory

$$C_3 = (g(h+H_s))^{1/2} \qquad (13)$$

These values overpredict the measured celerity by 20 percent.

As a final step, celerity was calculated as a function of frequency using equation (10) for linear wave theory. The wave number, k, was calculated from an iteration of the linear theory characteristic equation, equation (6). The resulting celerities, $C_4(f)$, are graphed in Figure (17). The decrease in celerity with increasing frequency, indicative of a dispersive wave system and expected with linear theory, would result in a corresponding increase in phase shift with frequency. This relationship was not observed; rather, the phase shift with frequency was constant as illustrated in Figure (16). The value for $C_4(f)$ at the primary frequency, 0.125 Hz, agreed well with the measured celerity, C_1 ($\pm$ 2 percent).

In summary, celerity calculations created a dilemma which future studies in the surf zone will have to resolve. The constant phase shift and measured celerity indicated that all frequency components are non-dispersive and ride on the back of a non-linear wave form moving at the speed C_1. However, linear wave theory predicted the horizontal velocity and both C_2 and C_4 (0.125Hz) closely approximate C_1. If linear theory is applicable, the wave system is dispersive or each component moves at a celerity which



CELERITY AT INTERMEDIATE POINTS BETWEEN STATIONS AS DESCRIBED BY C4 = σ/k
OUTER TO CENTER STATIONS
NON - DISPERSIVE, C1
DISPERSIVE, C4
C1
C2
OTHER PREDICTED CELERITIES
CELERITY (M/S)
4.0
3.0
2.0
1.0
0.2
0.4
0.6
0.8
CENTER TO INNER STATIONS
NON - DISPERSIVE, C1
DISPERSIVE, C4
CELERITY (M/S)
FREQUENCY (HZ)

Figure (17)

depends on its frequency. It appears that while linear theory can predict the relationships between waves it cannot be used to define the breaker zone wave form which is non-linear and non-dispersive.

F. COMMENTS ON INSTRUMENTS AND BEACH EXPERIMENT

As a corollary goal for this experiment, the instrumentation used and its placement in the surf zone was to be tested. The capacitance wave gages used were found to be reliable, inexpensive, hardy, and easily monitored in the surf zone. They were very accurate and appeared to give an excellent representation of wave profiles as they actually occurred. The work required to construct, calibrate, and install the gages was minimal. By mounting all electronics in a sealed container and running signal cables overhead, the chance of shorting the system and introducing noise was greatly reduced.

The use of electromagnetic flow meters in the surf zone gave excellent results. The lack of moving parts which clog with sand and the ability to record and monitor signals on the beach virtually eliminated the problem encountered by previous experimenters of incomplete or questionable records. Calibration of the flow meters was somewhat difficult and time consuming and required special equipment. A new calibration scheme should be devised to increase the calibration frequency range and accuracy. The results obtained were

sufficient for the experiment, however. Calibration of the flow meters is required as their response, although linear, deviated from the manufacturers specifications, showing both a slight DC bias and a different calibration slope.

The Baylor resistance wave gage also proved reliable, accurate, and very easy to calibrate. On the beach it was unwieldy and required a special tower to maintain tension on the cables. It was felt that the Baylor gage output was not as accurate as that obtained with the capacitance gages.

The selection of instrument locations on the beach was conducted four days prior to the actual measurements and was done by considering the beach profile and the location of breakers on that day. Wave gages were placed to span the breakers with the velocity measurements to be taken in the breaking waves. Fortunately, wave characteristics remained constant until the date of the experiment and placement was correct for the intended measurements.

The key word for the experiment setup was organization. The equipment and manpower requirements for an examination of surf zone kinematics using temporary stations can quickly become overwhelming. It is felt by the author that five to six measurements are maximum for a one-man experiment in the surf zone.

V. CONCLUSIONS

With the conditions of a mild surf and spilling breakers, linear wave theory was shown to predict wave kinematics well. Spectral analysis showed a good agreement between the measured horizontal water particle velocity spectrum and the horizontal velocity spectrum calculated using a linear theory conversion factor on the surface profile spectrum over the highly coherent band of prominent wave energy. A similar high coherence and the agreement with predicted phase relationships over the same band found in a cross-spectral analysis of the surface profile and vertical water particle velocity led the author to believe that a linear relationship, although not predictable by linear wave theory, also existed which relates the vertical velocity spectrum to the surface profile spectrum.

The shallow water approximation for celerity used in linear theory was an excellent prediction for wave phase speed in the experiment environment. A constant phase shift with frequency indicated the breaking waves were non-dispersive or that celerity was not frequency dependent. Apparently all energy rode on the back of a non-dispersive, and therefore non-linear, waveform which was at the primary frequency. An inconsistancy thus arose in that linear theory, a dispersive theory, could be used to predict wave kinematics; yet, celerity calculations all pointed to a

non-dispersive wave form. Future studies in the breaker zone are needed to resolve the question of linearity.

The use of capacitance wave gages and electromagnetic flow meters is a convenient method of gathering accurate, continuous data in the surf zone.

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